Probabilistic Asteroid Impact Risk Assessment
2023 PDC Hypothetical Impact Exercise
Scenario Epoch 1: Initial Discovery

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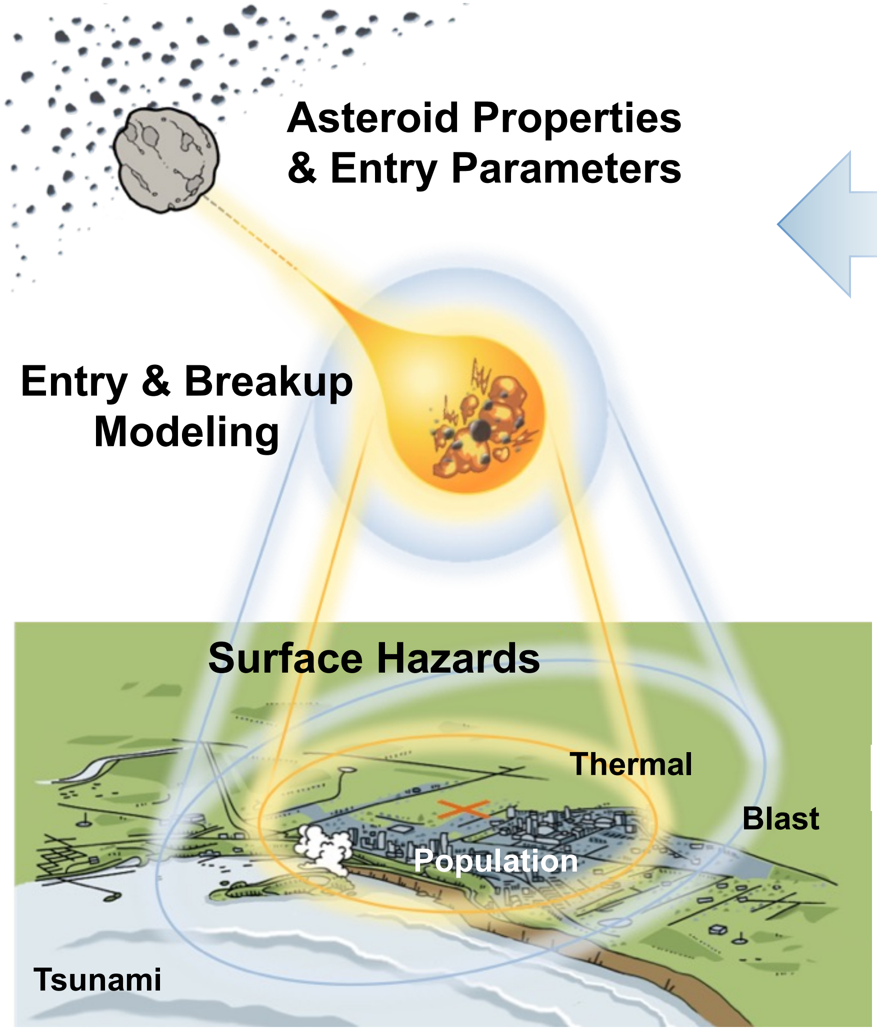
Asteroid Impact Threat Assessment

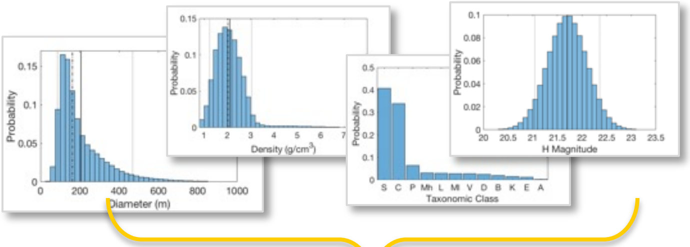
Probabilistic Asteroid Impact Risk (PAIR) Model



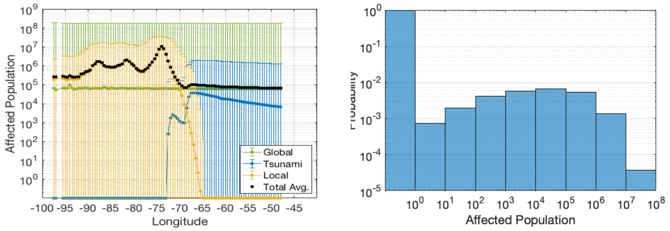
[PAIR model: Mathias et al., 2017; Stokes et al., 2017]

Impact Threat Scenario

Asteroid Property Distributions



Probabilistic Damage and Risk



- Risk model uses fast-running physics-based models to assess millions of impact cases representing the range of possible asteroid properties and impact locations.
- Atmospheric entry, breakup, and resulting hazards (blast, thermal, tsunami, global effects) are modeled for each case.
- Probabilities of the resulting damage sizes, severities, and affected populations are computed.
- Regions at-risk to local damage are mapped.

Impact Risk Summary

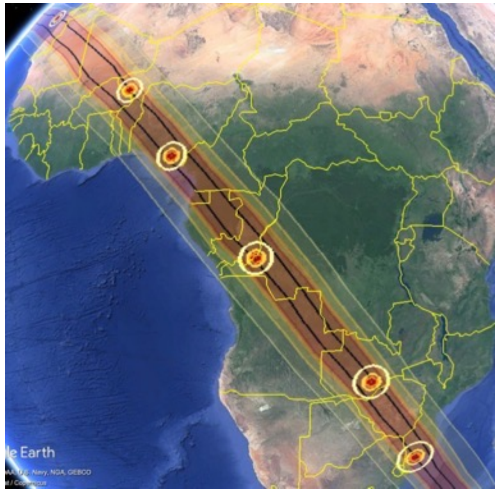
Assessment 1: Initial Discovery, 3 April 2023

Asteroid Characterization Summary

- Potential impact date: 22 Oct. 2036
- Earth impact probability: ~1%
- Initial observations indicate a very large, hazardous object, with large uncertainties in potential size range and other properties unknown
- Diameter: 150–2000 m (490–6560 ft), most likely 220–660 m (720–2160 ft), median size 470 m (1540 ft)
- Impact Energy: 54–160,000 megatons (Mt), most likely 54–55,000 Mt, median 230 Mt

Risk Region Swath Map

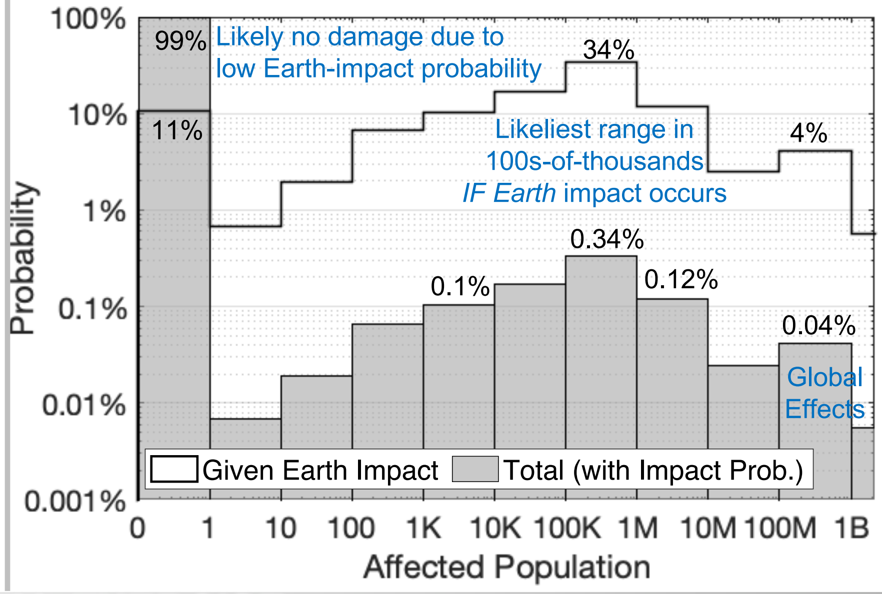
Regions potentially at risk, given range of damage locations and sizes. Median-sized damage areas are shown at sample locations.



Hazard Summary

- Large ranges of potential damage sizes, severities, and locations
- Asteroid is likely to miss Earth, but there is ~90% chance of potentially large population damage if impact occurs
- Impact would cause large blast & thermal damage reaching unsurvivable levels, with serious damage likely extending ~100–200 km (~60–120 mi) outward, and possibly out 600 km (370 mi) or more
- Large ocean impacts are likely to cause significant tsunami damage, especially across Atlantic regions or near coasts
- Largest possible sizes could cause catastrophic global-scale effects

Affected Population Risks



Probabilities of how many people could be affected by the potential damage

Range: 0–2B ppl

~240K total avg. risk (with ~1% Earth-impact probability)

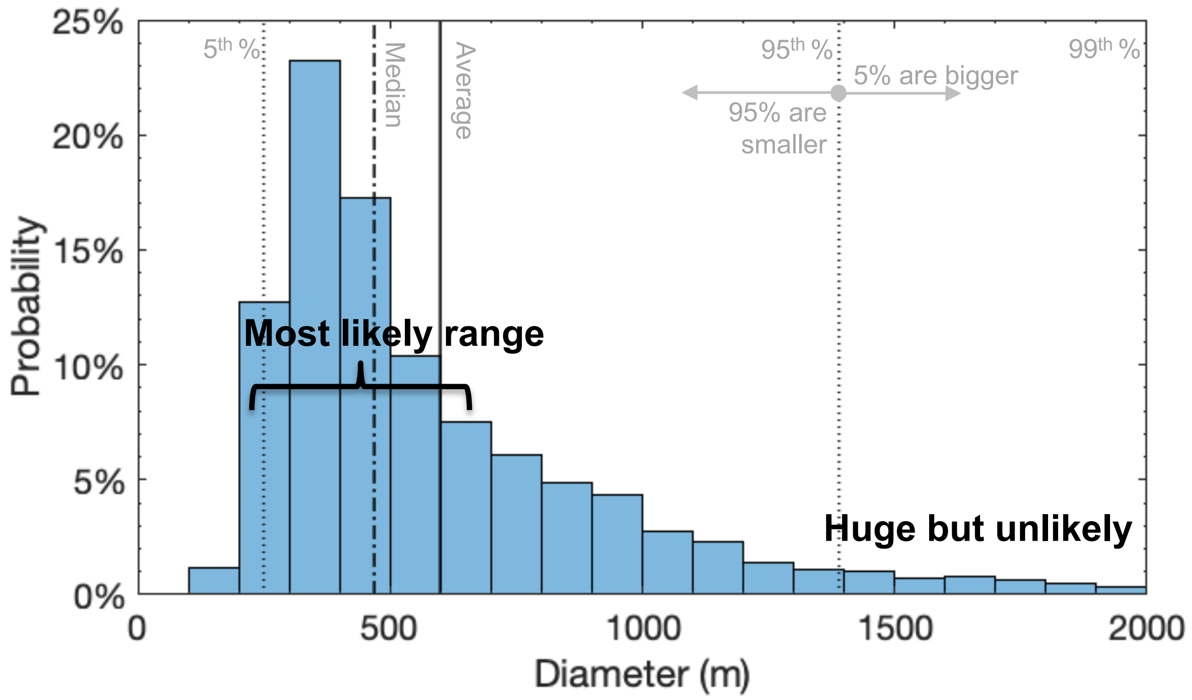
~24M avg. if Earth impact occurs

HYPOTHETICAL EXERCISE

Asteroid Size & Properties

- Asteroid size is hazardous but highly uncertain
  - Object brightness (H 19.4) indicates a large, hazardous impactor size, ranging from hundreds to thousands of meters in diameter
  - Most likely sizes are in the several-hundred-meter range
  - Kilometer-scale upper size range is catastrophically large but less likely
- Asteroid type and properties are unknown
  - Wide ranges of densities, strengths, structures, compositions
  - Ranging from more common stony types and rubble piles to rarer high-density iron types
  - (Property distributions given in appendix)
- Size and property uncertainties result in very large ranges of potential mass, energy, and damage

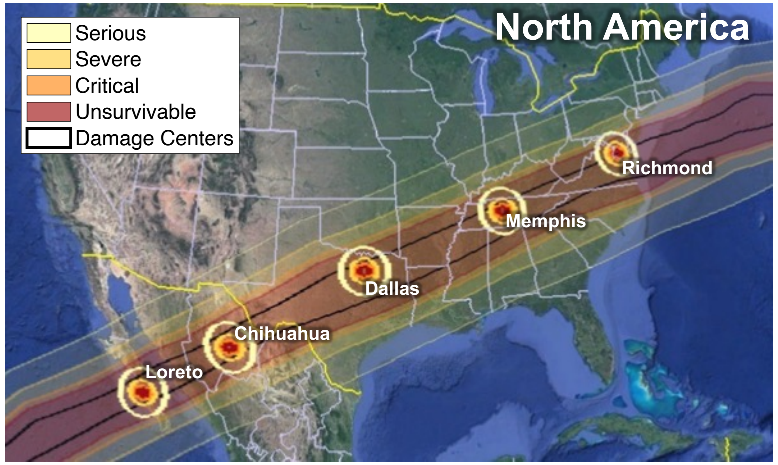
Asteroid Size Ranges & Probabilities

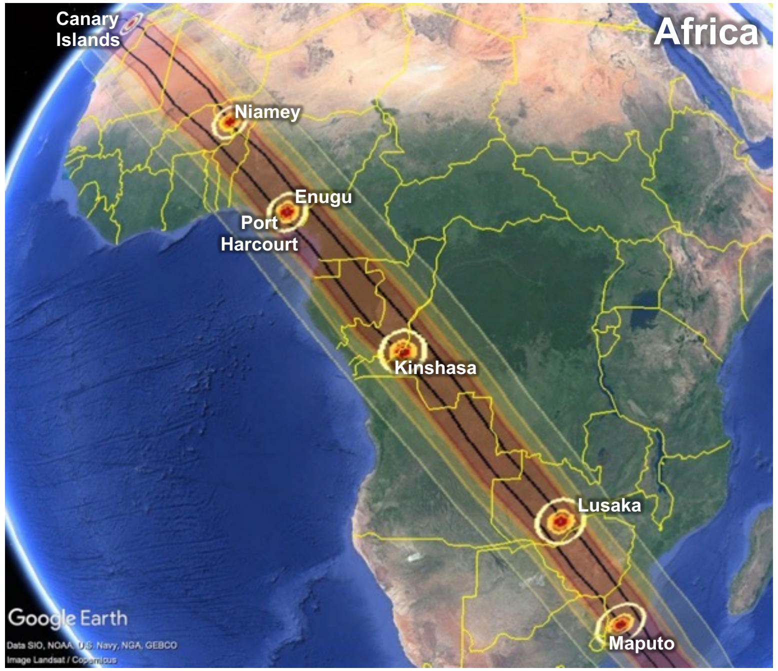


	Diameter	Mass	Energy
Median	470 m (1540 ft)	1.2e11 kg	230 Mt
Average	600 m (1950 ft)	6.0e11 kg	11,600 Mt
Most likely	220–660 m (720–2160 ft)	2.8e9–2.9e11 kg	54–5,500 Mt
Range	150–2000 m (490–6560 ft)	1.6e9–2.8e13 kg	54–160,000 Mt

[Property inference model: J. Dotson PDC 2021]

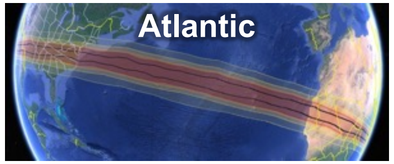
Damage Risk Swath

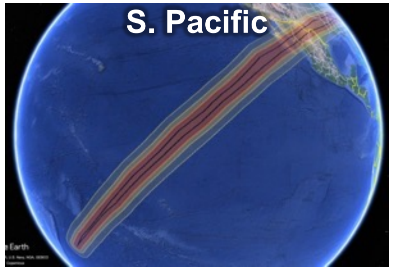




Damage risk swath: Shows extent of regions *potentially* at risk to *local ground damage**, given ranges of potential damage sizes and locations

(* Does not include regions potentially at risk to tsunami or global effects)



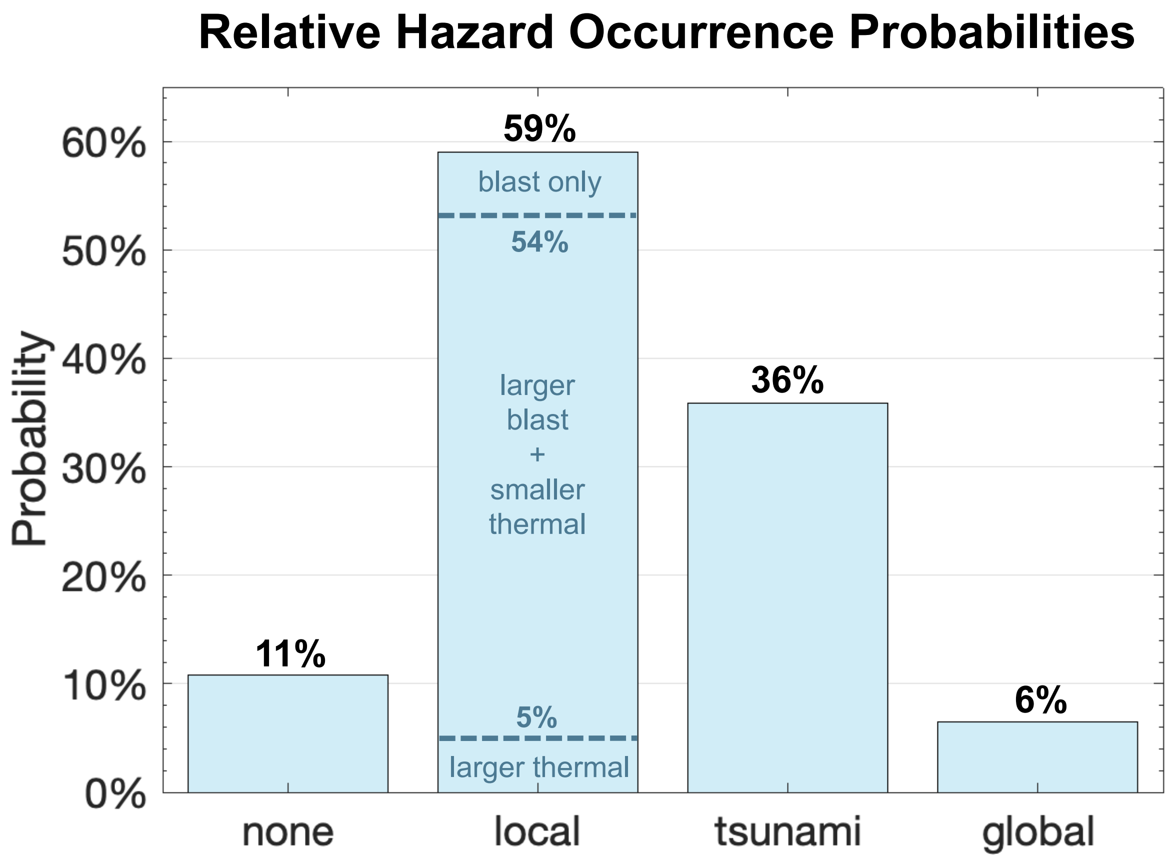


- Damage risk swath:
  - Black outline shows globe-spanning range of potential impact locations modeled (damage-center locations)
  - Shaded areas show potential extent of *local ground damage**, given range of impact sizes and locations, colored by damage severity level
  - Rings show median-sized damage footprints at sample locations
- Extent of current risk region:
  - Spans from the South Pacific to the southern Indian Ocean, crossing Mexico, U.S., and Africa.
  - Impact corridor is ~200-300 km (~150 mi) wide
  - Potential damage regions extend ~1000 km (~600 mi) across
  - Extent of potential impact locations will shrink as observations refine the orbital data
  - Extent of damage range could also shrink if missions or observations can constrain asteroid size or type

Hazard Sources

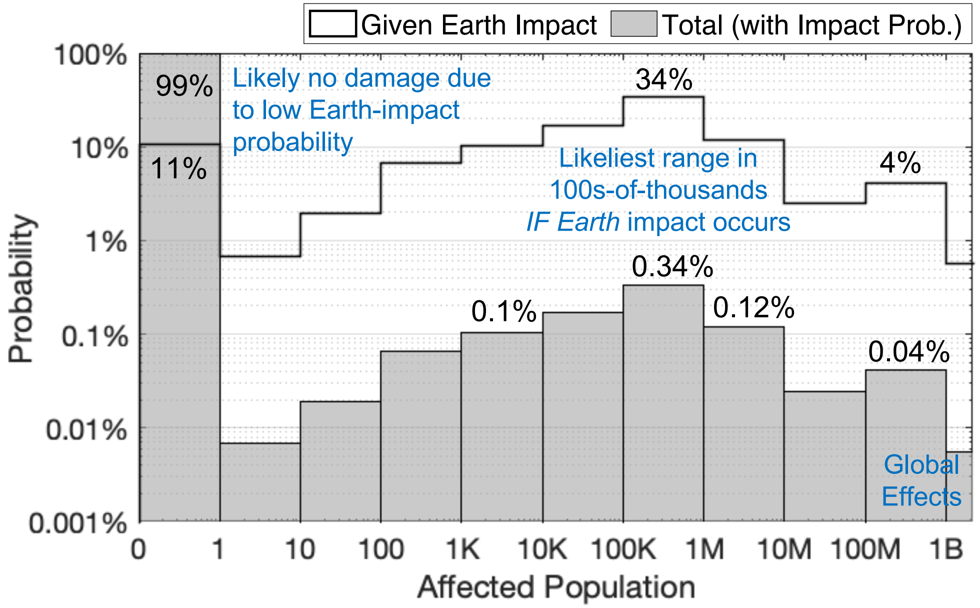
Relative hazard probabilities among ~1% of Earth-impacting cases

- 52% chance of impact over land, 48% water
- All impacts over land cause large local blast and/or thermal ground damage affecting populated areas
  - Blast damage occurs in ~60% of all Earth-impact cases, and 100% of cases over land or shore.
  - Thermal damage also occurs in ~54% of cases, but is only greater than blast damage in ~5%
- Tsunami damage occurs in ~74% of ocean cases (36% of all cases)
- Largest impactors could cause catastrophic global-scale effects in ~6% of cases
- Potential for regional environmental effects from larger sub-global impacts is unknown
- No damage occurs in ~11% of Earth-impact cases (smallest sizes over ocean)



* A single impact event can cause multiples hazards (e.g., blast + thermal, tsunami + local near-shore, or global + local or tsunami). Sum of all hazard occurrence probabilities may exceed 100%.

Affected Population Risks



Population Risk Histogram: Probabilities of affecting the number of people within each range

Minimum Affected Population	Probability if Earth-Impact Occurs	Total Probability (with Earth-impact)
Any	89%	1.0%
>1K	80%	0.8%
>10K	70%	0.7%
>100K	53%	0.5%
>1M	19%	0.2%
>10M	7%	0.07%
>100M	5%	0.05%
>1B	~0.6%	0.006%

Population Exceedance Risks: Probabilities of affecting ***at least*** the given number of people *or more*

- **Low chance of Earth-impact, but high chance of significant damage if impact occurs:**
  - <1% chance of damage when including the Earth-impact probability of ~1%
  - 89% chance of damage if Earth-impact occurs, most likely affecting hundreds-of-thousands of people
- **Average affected population risk:**
  - ~240K total avg. (with ~1% impact probability)
  - ~24M avg. among Earth-impacting cases
- **Probabilities of large population damage:**
  - Chance of affecting **over 100K** people: ~**0.5%** total, **53%** given impact
  - Chance of affecting **over 1M** people: ~**0.2%** total, **19%** given impact
  - Chance of affecting **over 10M** people: ~0.07% total, 7% given impact
  - Up to ~**100M–2B** people estimated for largest potential global effects

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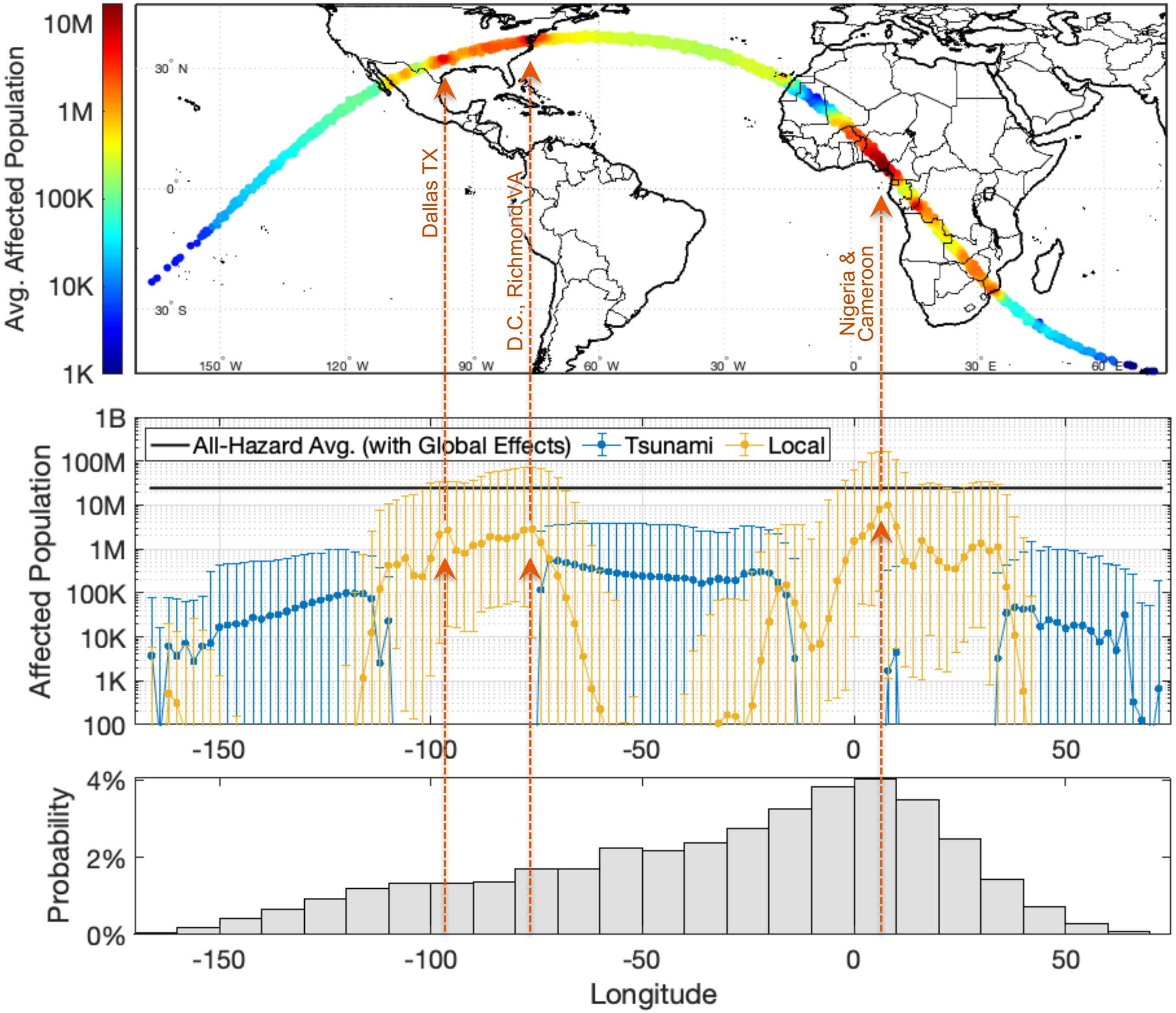
Population Damage Ranges Along Swath

- Impacts over land cause most population damage
  - Average local affected population ranges are 10K-10M across Africa and 100K-3M across US
  - Maximums reach ~10M-100M
- Significant tsunami may be possible across all ocean regions if impact is large
  - Average tsunami affected population ranges are ~10K–600K
  - Greatest tsunami risks are near-shore Atlantic impacts (near US East coast, W. Africa coast)
- Near-shore impacts can cause both blast and/or tsunami damage
- Highest impact risk region is Nigeria & Cameroon with an average affected pop of ~10M



Average affected population: Average for each potential entry point, given range of potential asteroid sizes and properties

Affected population ranges: Averages and min/max ranges within 2° longitude increments along swath

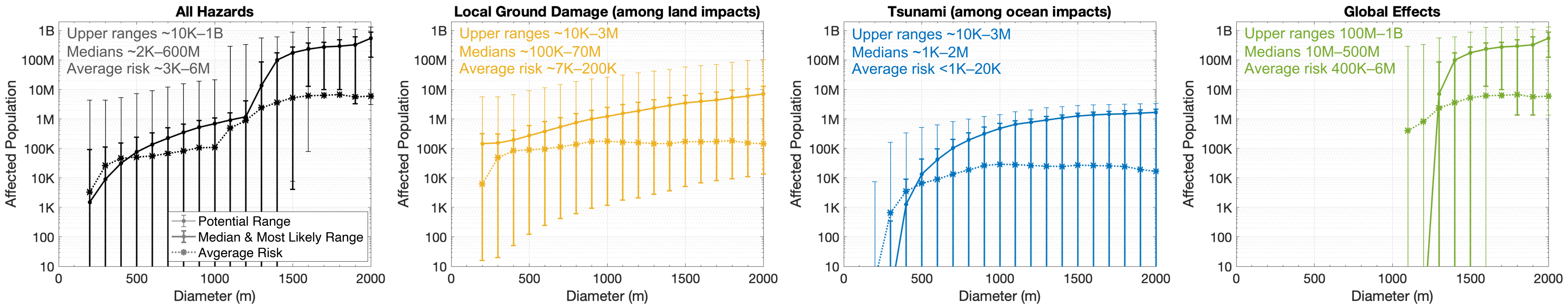
Relative impact probability: among potential swath regions, given an Earth-impact

Hazard Damage Ranges By Asteroid Size

- Large range of potential asteroid sizes yields large ranges of potential damage. Each asteroid size could also produce a wide range of potential population damage due to different impact locations and other unknown asteroid properties (such as density and strength) that affect impact energy and hazard factors.
- **Significant population damage is likely across all potential asteroid sizes.** Largest possible asteroid sizes would cause extreme population damage across all hazards, but are also relatively less likely compared to smaller asteroid sizes
- The ***average risk*** for each size range (plotted as asterisks) scales the average affected population of each asteroid size by the relative likelihood of that size range.
- **Global Effects** pose largest average risk levels, even given low-probability of kilometer-scale asteroid sizes
- **Tsunami** risk & damage levels increase most for sizes 400-1000m and level off for larger sizes
- **Local damage** & risk ranges (among land case) are greater than tsunami ranges (among ocean cases) for all asteroid sizes

Affected Population Ranges by Asteroid Size for each Hazard Type

Potential Range   Median & Most Likely Range   Avgerage Risk



HYPOTHETICAL EXERCISE

Summary

- **Risk assessment indicates significant potential damage sizes, severities, and risk probability levels across all potential asteroid size ranges, impact locations, and impact hazards**
  - Total risk levels are significantly high, even with low current impact probability
  - Extreme global damage risks posed by largest possible impact sizes drives risk levels and should not be disregarded, despite the lower probability of occurrence
  - Local damage areas from even the smaller and moderate range of impact sizes would require large-scale evacuation, civil defense, and infrastructure protection measures over very large areas
  - Ocean impacts also could pose substantial tsunami risks across large coastal regions. Additional simulation is recommended to better assess these hazards
- **Recommendations:**
  - If orbital observations confirm likely Earth strike, reconnaissance missions and additional observations are needed as soon as possible to refine size range and prepare mitigation measures to deflect or disrupt potentially large objects early enough
  - Additional modeling & simulation studies of large-scale impact effects are recommended to better assess potential damage levels, given current model uncertainties in these regimes

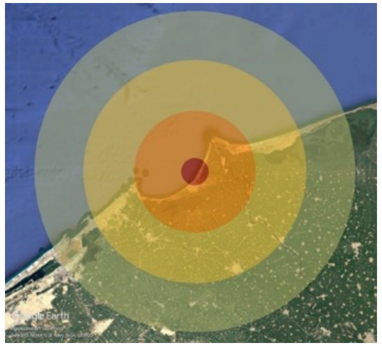
	Total Average Population Risk (with Earth-impact probability)	**Chance of Hazards Causing Damage** (if impact occurs)	**Affected Population Ranges (among applicable Earth-impacting cases)**				
			Average	Median	95th%	99th%	Largest worst-case modeled
All Hazards	243K	89%	24.3M	130K	87M	784M	2B
Global Effects	237K	6%	23.7M	0	86M	784M	2B
Local Blast/Thermal (Land)	9K	100%	1.7M	320K	7M	24M	166M
Tsunami (Ocean)	1K	74%	200K	10K	1M	2M	4M

HAZARD DAMAGE & RISK DETAILS:

LOCAL BLAST & THERMAL DAMAGE
TSUNAMI DAMAGE
GLOBAL EFFECTS

Local Blast & Thermal Damage Effects

- Large impacts and airburst can generate destructive blast waves and thermal heat radiation that can cause various levels of injury, fatalities, structural damage, and/or fires extending far around the impact location.
- Blast and thermal ground damage are assessed *independently* at four equivalent severity levels
  - The damage region for each severity level is determined from the *larger* of the equivalent blast *or* thermal damage area
  - Local ground damage regions indicate *either* blast or thermal effects could exceed the given severity threshold (*not* necessarily the occurrence of both effects within the entire region)
  - Local affected population estimates within each region are scaled by the relative severity of each damage level
- Blast is the predominant hazard for most asteroid sizes
  - Blast tends to be larger and more severe than the potential thermal damage in most cases, and usually define the larger outer serious and severe risk regions for emergency response planning
  - Critical and unsurvivable thermal damage areas can be larger than equivalent blast levels for the larger impact sizes



Damage Level	Relative Severity	Blast Damage Effects	Thermal Damage Effects
Serious	10%	Shattered windows, some structural damage	2nd degree burns
Severe	30%	Widespread structural damage	3rd degree burns
Critical	60%	Most residential structures collapse	Clothing ignites
Unsurvivable	100%	Complete devastation	Structures ignites, incineration

HYPOTHETICAL EXERCISE

Local Blast & Thermal Damage Area Sizes

- Most likely local hazard is a large ground impact causing a highly destructive blast wave and thermal fireball from the entry and impact
  - Significant blast damage is certain to occur, ranging from unsurvivable levels to shattered windows and structure damage over large areas
  - Significant thermal damage is also nearly certain to occur, most likely reaching unsurvivable levels
  - Thermal damage tends to be smaller than the corresponding blast regions, but largest impactors may cause larger thermal damage areas
- Uncertain asteroid size and properties result in a large range of possible damage sizes
  - Most likely outer damage radius range is ~85–200 km (53–130 mi)
  - Largest outer damage areas could extend out ~600 km (~370 miles) or more in radius

Potential Blast Damage Severities and Sizes

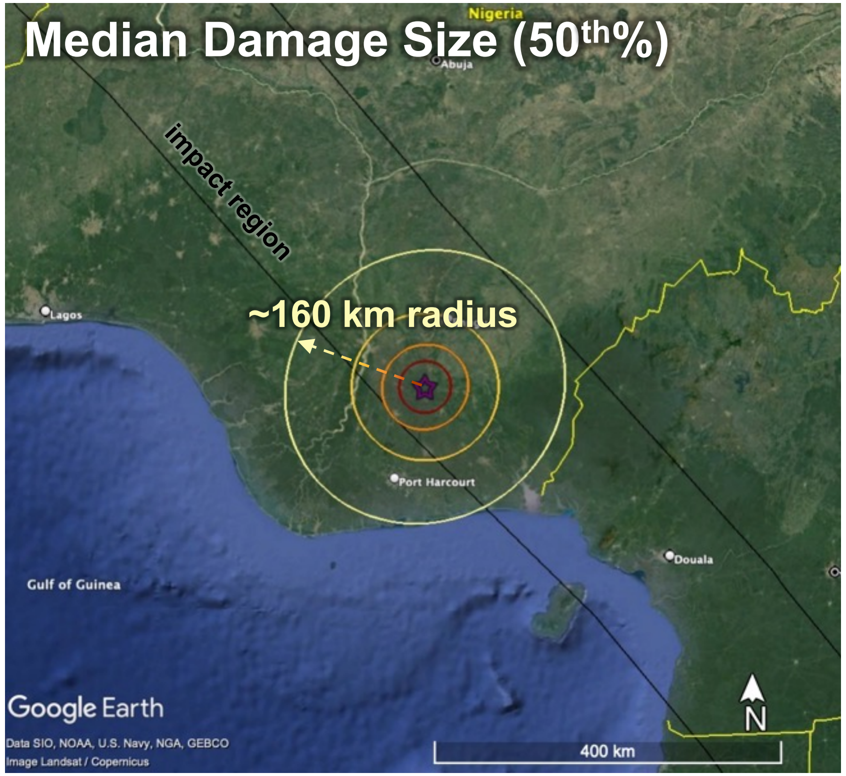
Damage Level	Potential Blast Effects	Chance of Occurring	Damage Radius Ranges (km)		
			Median	Most Likely	Range
Serious	Shattered windows, some structure damage	100%	160	85–210	70–570
Severe	Widespread structure damage	100%	85	45–110	40–330
Critical	Most residential structures collapse	100%	50	25–65	20–180
Unsurvivable	Complete devastation	100%	25	15–35	10–100

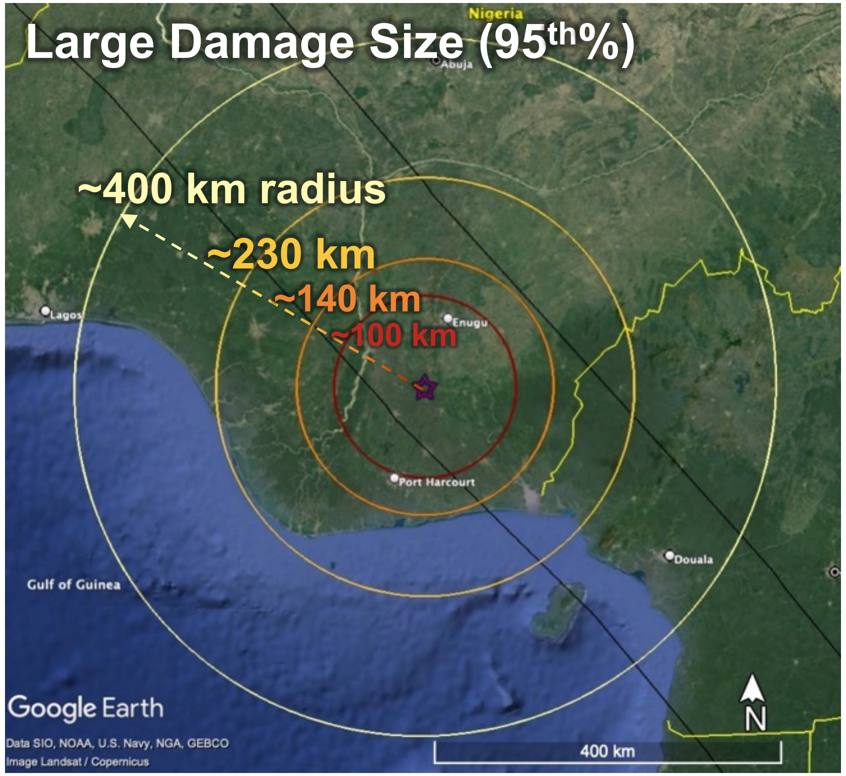
Potential Thermal Damage Severities and Sizes

Damage Level	Potential Thermal Effects	Chance of Occurring	Damage Radius Ranges (km)		
			Median	Most Likely	Range
Serious	2nd degree burns	99%	44	6–80	0–430
Severe	3rd degree burns	98%	34	0–60	0–330
Critical	Clothing ignition	96%	24	0–40	0–230
Unsurvivable	Structure ignition	95%	20	0–30	0–200

Sample Ground Damage Sizes over Nigeria

(highest population damage location along swath)





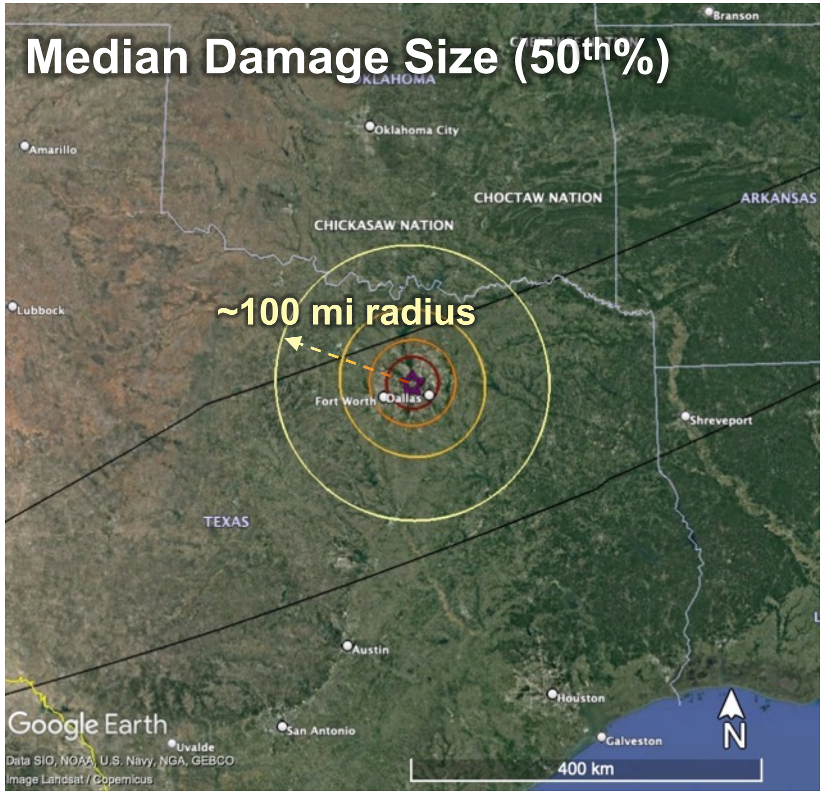
- Rings show sample damage footprint sizes at a single sample location
- Black border shows range of potential impact locations (damage center points) along swath
- Percentiles give the chance that the damage region could be up to the given size or smaller

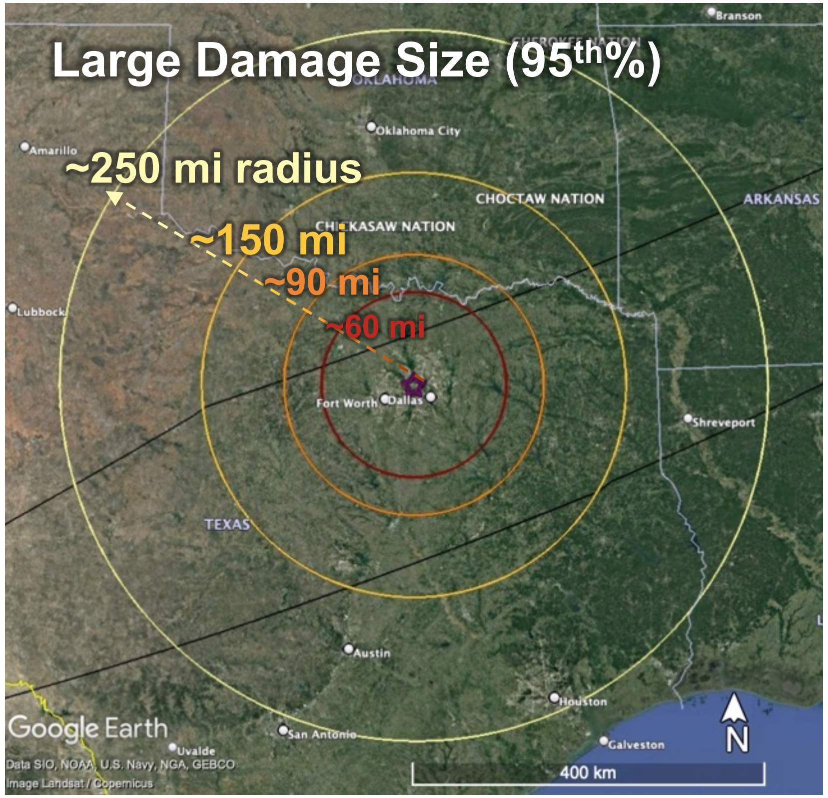
Local Ground Damage Radius Sizes (km / mi)

Damage Level	Mean	25th %	**50th %**	75th %	**95th %**
Serious	190 km (120 mi)	120 km (75 mi)	**160** km (100 mi)	220 km (140 mi)	**400** km (250 mi)
Severe	110 km (70 mi)	70 km (45 mi)	**90** km (55 mi)	120 km (75 mi)	**230** km (150 mi)
Critical	65 km (40 mi)	40 km (25 mi)	**50** km (30 mi)	75 km (45 mi)	**140** km (90 mi)
Unsurvivable	40 km (25 mi)	20 km (15 mi)	**30** km (20 mi)	50 km (30 mi)	**100** km (60 mi)

	Damage Level Description
	Windows shatter, minor structure damage
	Widespread structure damage, or 3rd degree burns
	Residential structures collapse, or clothing ignites
	Devastation, structures flattened or burned

Sample Ground Damage Sizes over Dallas TX
(highest US population damage location)





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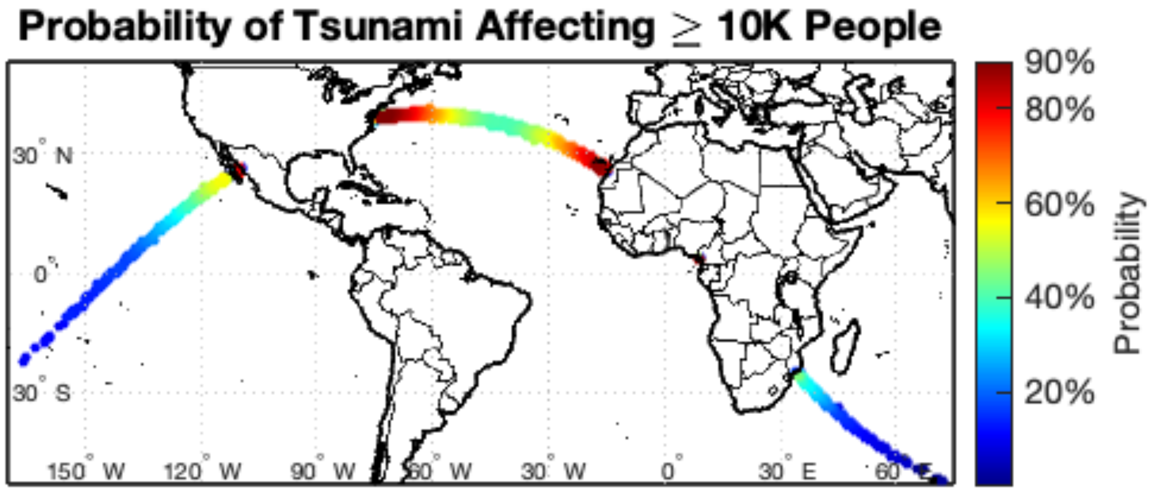
Tsunami Risk & Damage

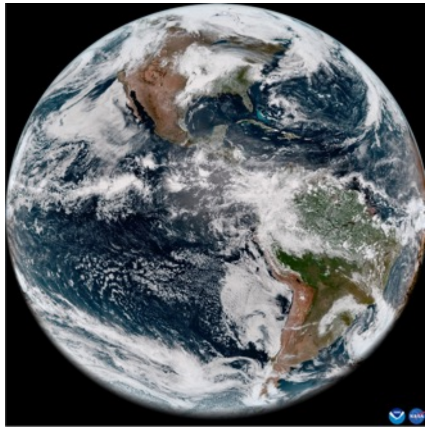
- 48% of potential swath impact regions are over ocean
- Tsunami damage occurs in ~74% of ocean cases (36% of all impact cases)
- High chance of large tsunami from impacts across all Atlantic regions or near coasts of Mexico or SE Africa
    - Impacts near US East coast or West African coast pose greatest tsunami damage risks
    - Significant tsunami are less likely for S. Pacific or Indian Ocean regions further than ~800–1000 km (~500–600 mi) offshore
- Tsunami population risks (among ocean impacts):
    - Average affected population ranges are 10K–620K among most ocean points (200K avg. over all ocean points)
    - 50% chance of large tsunami affecting >10K people (40–90% chance across all Atlantic points)
    - Largest tsunami could affect up to millions of people

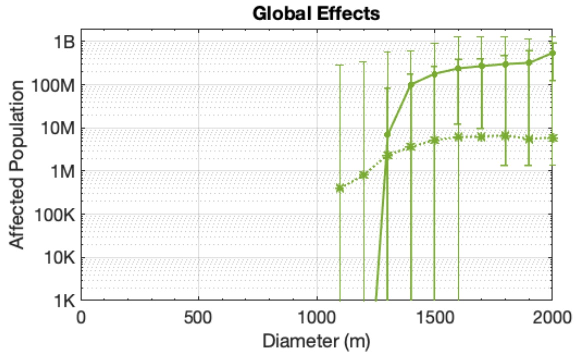


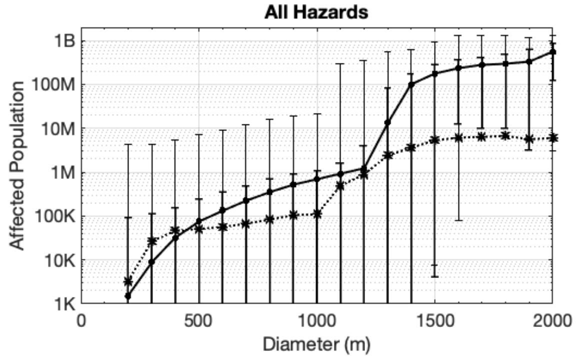
- ***Additional tsunami & inundation modeling is recommended***
    - Tsunami risk model provides **pessimistic low-fidelity estimates** of potential tsunami effects, but large uncertainties remain in current results
    - Potential for significant tsunami risk **warrants further higher-fidelity modeling** to better determine potential tsunami generation, propagation, and inundation levels for these different asteroid sizes and ocean regions

Global Effects (GE)

- The largest potential impacts could produce enough atmospheric ejecta to cause global climatic effects, potentially affecting substantial fractions of the world population
  - 6% chance of global effects from large asteroids with impact energies between 40–160 gigatons (diameters over ~1 km or 3300 feet, depending on density and entry velocity)
- Global effects drive greatest average population risk levels despite low probability
  - Although these large sizes are relatively unlikely, the potential consequences are extreme and pose a high level of risk
  - Affected population estimates for these sizes are in the tens-of-millions to hundreds-of-millions, with worst-case estimates affecting over a billion (~20-25% of world population)
  - Average GE affected population 24M people (among all Earth-impacting cases)
  - Total average GE population risk is 260K people (including ~1% Earth-impact probability)
- Current GE risk models are highly uncertain, providing only rough estimates of global population fractions affected, based on impact energy.
  - Large uncertainties remain in what asteroid sizes may start to cause onset of these effects, amounts of ejecta, and severity or specifics of resulting climate effects.
  - Potential for other cascading regional, environmental, or socioeconomic effects from large sub-global-scale impacts is currently unknown, and not included in current risk modeling.
  - Additional simulations and studies of these large impactors and hazards are recommended.







ASTEROID PROPERTY & ENTRY DETAILS:

ASTEROID PROPERTY DISTRIBUTIONS
ATMOSPHERIC ENTRY PARAMETERS

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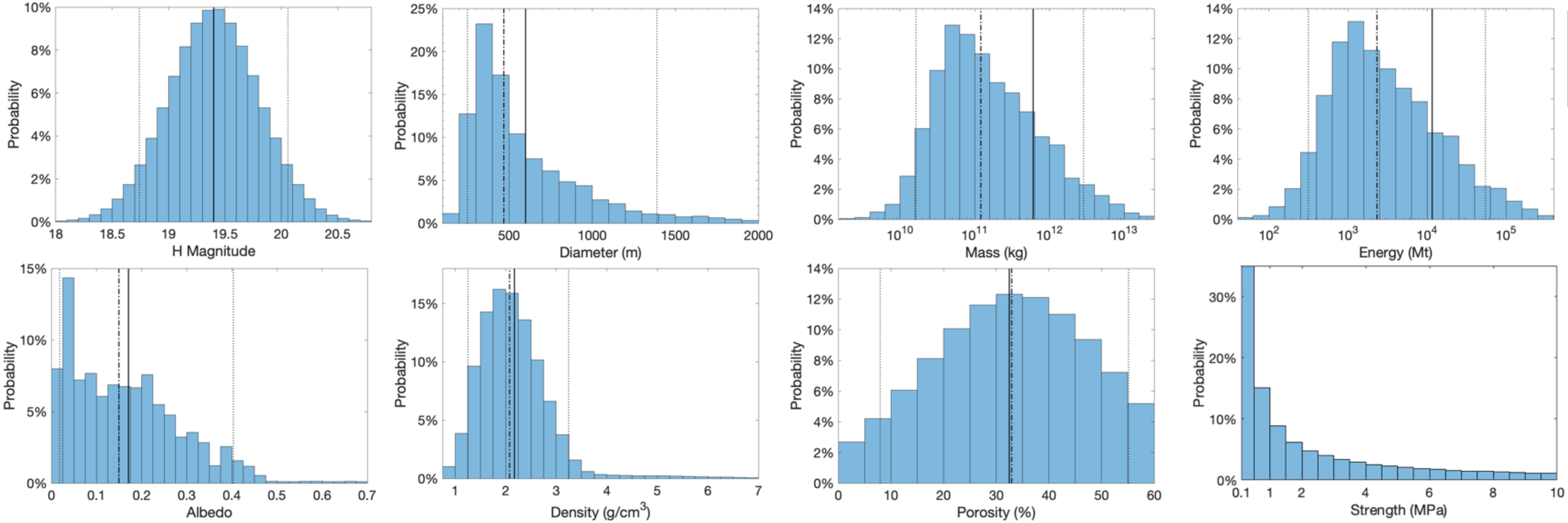
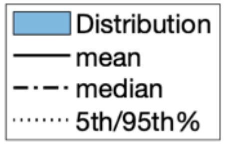
NASA

Asteroid Property Details

Statistical percentiles and highest-probability interval ranges for asteroid property distributions*

	Mean	5th%	25th%	Median (50th%)	75th%	95th%	Most Likely Range (68%)	Potential Range (99%)
Diameter (m)	600	250	347	469	738	1389	216 – 660	151 – 2000
Mass (kg)	6.0E+11	1.6E+10	4.7E+10	1.2E+11	4.2E+11	2.8E+12	2.8E+09 – 2.9E+11	2.8E+09 – 8.4E+12
Energy (Mt)	1.2E+04	3.1E+02	9.0E+02	2.3E+03	8.1E+03	5.5E+04	5.4E+01 – 5.5E+03	5.4E+01 – 1.6E+05
H Magnitude	19.40	18.75	19.13	19.40	19.67	20.07	19.02 – 19.82	18.34 – 20.4
Albedo	0.17	0.02	0.05	0.15	0.24	0.40	0.01 – 0.21	0.01 – 0.67
Density (g/cm^3)	2.2	1.3	1.7	2.1	2.5	3.3	1.4 – 2.6	0.8 – 5.3
Porosity (%)	32%	8%	22%	33%	43%	55%	18% – 49%	1.8% – 60%
Strength (MPa)	2.2	0.1	0.3	1.0	3.2	8.0	0.1 – 2.4	0.1 – 10



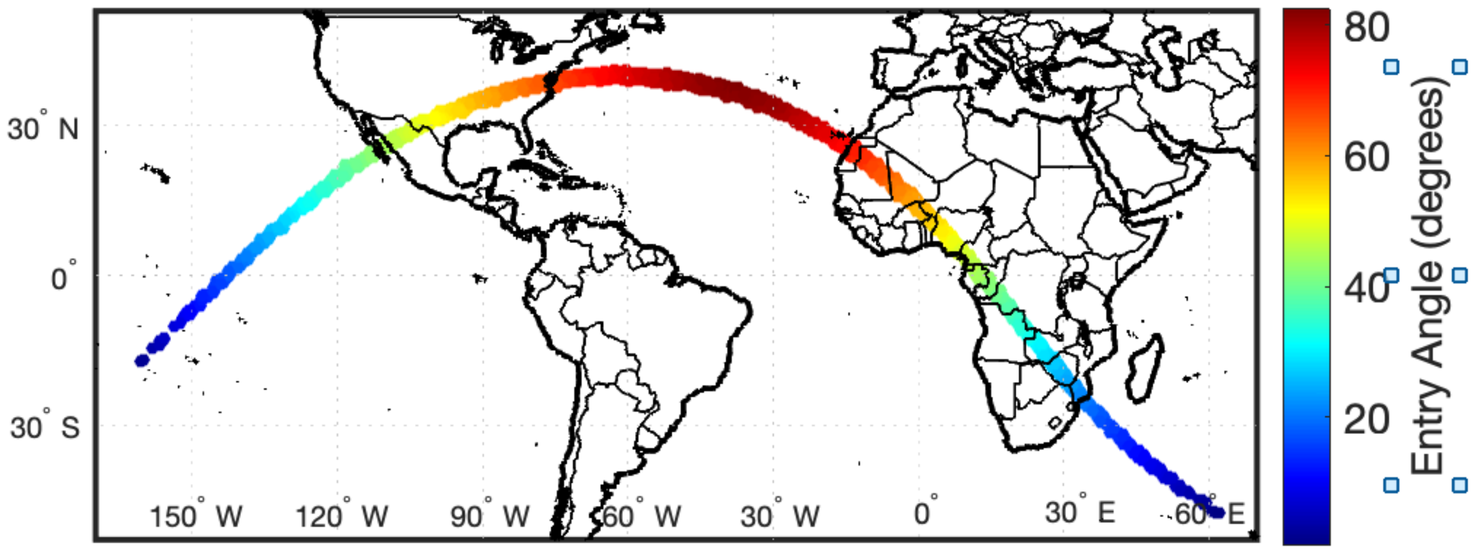


* Property stats are each computed *independently*. Multiple values from a given percentile cannot necessarily be combined to represent a single physically-plausible asteroid.

Entry Parameters & Locations

- Around 1% chance of Earth impact somewhere along a globe-spanning corridor from the South Pacific, across North America, Atlantic, Africa, and into the southern Indian Ocean.
- Entry parameters vary across the corridor, but are well-known for given impact points
- **Entry Velocity:**
  - 12.67–12.68 km/s
  - Little variation across swath
- **Entry Angle:**
  - Nearly-vertical entries (83°) in mid-Atlantic
  - Shallow skimming entries near edges
- **Entry Direction (CW from N):**
  - Entry direction rotates along swath
  - Southward over mid-Atlantic (90°)
  - SEbS at eastern edge (122°)
  - SW at western edge (225°)

Entry Angle (from horizontal)



[Impact entry data: P. Chodas, CNEOS/JPL, https://cneos.jpl.nasa.gov/pd/cs/pdc23/

REFERENCES

ATAP Impact Risk Modeling Papers

Probabilistic Asteroid Impact Risk (PAIR) Model

- **Mathias et al., 2017.** A probabilistic asteroid impact risk model: assessment of sub-300m impacts. Icarus 289, 106–119. https://doi.org/10.1016/j.icarus.2017.02.009
- **Stokes et al., 2017.** Update to determine the feasibility of enhancing the search and characterization of NEOs. National Aeronautics and Space Administration. https://www.nasa.gov/sites/default/files/atoms/files/2017_neo_sdt_final_e-version.pdf
- **Wheeler & Mathias, 2018.** Probabilistic assessment of Tunguska-scale asteroid impacts. Icarus, 327, 83–9. https://doi.org/10.1016/j.icarus.2018.12.017
- **Rumpf et al., 2020.** Deflection driven evolution of asteroid impact risk under large uncertainties. Acta Astonautica 176, 276–286. https://doi.org/10.1016/j.actaastro.2020.05.026
- **Reddy et al., 2022.** Apophis planetary defense campaign. Planetary Science Journal, 3:123 (16pp). https://doi.org/10.3847/PSJ/ac66eb
- **Reddy et al., 2022.** Near-Earth Asteroid (66391) Moshup (1999 KW4) Observing Campaign: Results from a Global Planetary Defense Characterization Exercise. Icarus 374, 114790. https://doi.org/10.1016/j.icarus.2021.114790
- **Reddy et al., 2019.** Near-Earth Asteroid 2012 TC4 Campaign: results from a global planetary defense exercise. Icarus 326, 133–150. https://doi.org/10.1016/j.icarus.2019.02.018

Entry & Breakup Energy Deposition Modeling

- **Wheeler et al., 2018.** Atmospheric energy deposition modeling and inference for varied meteoroid structures. Icarus 315, 79–91. https://doi.org/10.1016/j.icarus.2018.06.014
- **Wheeler et al., 2017.** A fragment-cloud model for asteroid breakup and atmospheric energy deposition. Icarus 295, 149–169. https://doi.org/10.1016/j.icarus.2017.02.011
- **Register et al., 2020.** Interactions between asteroid fragments during atmospheric entry. Icarus 337, 113468. https://doi.org/10.1016/j.icarus.2019.113468

Blast Modeling and Simulation

- **Aftosmis, et al., 2019.** Simulation-based height of burst map for asteroid airburst damage prediction. Acta Astronautica 156, 278-283. https://doi.org/10.1016/j.actaastro.2017.12.021
- **Robertson & Mathias, 2019.** Hydrocode simulations of asteroid airbursts and constraints for Tunguska. Icarus 327, 36–47. https://doi.org/10.1016/j.icarus.2018.10.017
- **Aftosmis, et al., 2016.** Numerical simulation of bolide entry with ground footprint prediction. 54th AIAA Aerospace Sciences Meeting. https://doi.org/10.2514/6.2016-0998

Thermal Radiation Modeling and Simulation

- **Johnston et al., 2021.** Simulating the Benešov bolide flowfield and spectrum at altitudes of 47 and 57 km. Icarus 354, 114037. https://doi.org/10.1016/j.icarus.2020.114037
- **Johnston & Stern, 2018.** A model for thermal radiation from the Tunguska airburst. Icarus, 327, 48–59. https://doi.org/10.1016/j.icarus.2019.01.028
- **Johnston et al., 2018.** Radiative heating of large meteoroids during atmospheric entry. Icarus 309, 25–44. https://doi.org/10.1016/j.icarus.2018.02.026

Tsunami Simulations

- **Robertson & Gisler, 2019.** Near and far-field hazards of asteroid impacts in oceans. Acta Astronautica 156, 262–277. https://doi.org/10.1016/j.actaastro.2018.09.018
- **Berger & Goodman, 2018.** Airburst-generated tsunamis. Pure Appl. Geophys. 175 (4), 1525-1543. https://doi.org/10.1007/s00024-017-1745-1
- **Berger & LeVeque, 2018.** Modeling issues in asteroid-generated tsunamis. NASA Contractor Report NASA/CR-2018-219786. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20180006617.pdf

Prior Related PDC 2021 Presentations

PDC 2021 presentation recordings and materials available at:

https://www.unoosa.org/oosa/en/ourwork/topics/neos/2021/IAAPDC/index.html

https://atpi.eventsair.com/QuickEventWebsitePortal/7th-iaa-planetary-defense-conference-2021/website/Agenda

https://cneos.jpl.nasa.gov/pd/cs/pdc21/day1.html

PDC 2021 Impact Exercise Risk Assessment

- **Wheeler** et al., "2021 PDC Hypothetical Impact Exercise: Probabilistic Asteroid Impact Risk Scenario Day 1" (Day 1 Exercise Session)
- **Wheeler** et al., "2021 PDC Hypothetical Impact Exercise: Probabilistic Asteroid Impact Risk Scenario Day 3" (Day 3 Exercise Session)

Asteroid Property Inference

- **Dotson** et al., "Bayesian Inference of Asteroid Physical Properties: Application to Impact Scenarios" (Impact Effects Session 9b)
- **Kelley** et al., "IAWN Planetary Defense Exercise: Apophis Observing Campaign 2020-2021" (Apophis Session 13)

Impact Effects – Hazard Modeling & Simulation

- **Aftosmis** et al., "High-Fidelity Blast Modeling of Impact from Hypothetical Asteroid 2021 PDC" (Impact Effects e-lighting talks)
- **Wheeler** et al., "Probabilistic Blast Damage Modeling Uncertainties and Sensitivities" (Impact Effects e-lighting talks)
- **Mathias** et al., "Interaction of Meteoroid Fragments During Atmospheric Entry" (Impact Effects e-lighting talks)
- **Coates** et al., "Comparison of Thermal Radiation Damage Models and Parameters for Impact Risk Assessment" (Impact Effects e-lighting talks)
- **Berger** and LeVeque, "Towards Adaptive Simulation of Dispersive Tsunami Propagation from an Asteroid Impact" (Impact Effects Session 9b)
- **Titus** et al., "Asteroid Impacts – Downwind and Downstream Effects" (Impact Effects Session 9b)

Mitigation & Mission Design

- **Barbee** et al., "Risk-Informed Spacecraft Mission Design for the 2021 PDC Hypothetical Asteroid Impact Scenario" (Mission & Campaign Design Session 8b)